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Recent Developments in Photometry and Colorimetry

By G. T. WINCH, M.I.E.E., F.Inst.P. *(Fellow)*.

Abstract

New tungsten filament secondary standard lamps are described and also tubular fluorescent secondary standards which, when used in an international photometric and colorimetric interchange, showed good agreement on measurements. Possible improved future changes in the C.I.E. data and the effect these may have on photometric and colorimetric values are indicated New developments in physical photometry and colorimetry are described, including preliminary experience with photon counting techniques as a means of increasing sensitivity. Improved photometric integrator paint is described, as this is now necessary in order to meet the new accuracy requirements. Brief reference is made to colour-rendering properties of light sources in connection with attempts to relate this subjective effect with objective measurements. The future possibility of applying ultrasonic modulation to colour measurement is indicated.

(1) Introduction

In recent years, following new requirements for higher accuracy of measurement, there have been considerable improvements in photometry and colorimetry in respect of systems, methods, techniques and instruments. Space will not permit a complete review of these developments and therefore the present paper will deal only with the more important advances relating to the measurement of directional intensity, luminous flux, colour and objective colour-rendering properties of light sources. These have special significance in connection with the measurement and specification, both nationally and internationally, of the characteristics of tubular fluorescent and other electric discharge lamps.

In 1949, the author described elsewhere[1] the problems which arise in the establishment of units and scales for the accurate measurement of light and colour. He also described and appraised visual and physical photometric and colorimetric techniques which had been developed up to that time. In the present paper, therefore, as indicated by the title, only recent developments in photometry and colorimetry will be considered.

(2) Secondary Standard Lamps

In both visual and physical photometric and colorimetric techniques, calibration must be made by reference to standards. It is therefore necessary in the present paper to include reference to developments in secondary standard lamps because of the important part they play in connection with the accuracy of photometry and colorimetry.

In 1948, the primary standard of light, which is reproducible from specification, became the international standard of reference. The setting up of this standard, however, involves elaborate apparatus and techniques suited only to photometric standardising laboratories, usually the national laboratories. There continues, therefore, to be a need for secondary standard lamps, calibrated in terms of the primary standard, for use in calibrating photometers and colorimeters. The steadily increasing precision being achieved in photometry and colorimetry, mainly as the result of the extensive use of sensitive physical methods of measurement, has resulted in a requirement for

Communication from the Staff of the Research Laboratories of The General Electric Company Limited, Wembley, England. The manuscript of this paper was first received on November 28, 1955, and in revised form on December 16, 1955. The paper was presented at a meeting of the Society held in London on January 10, 1956.

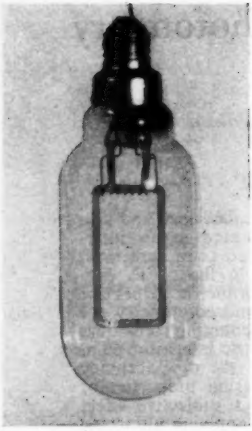

Fig. 1 (above). Uniplane vacuum standard lamp.

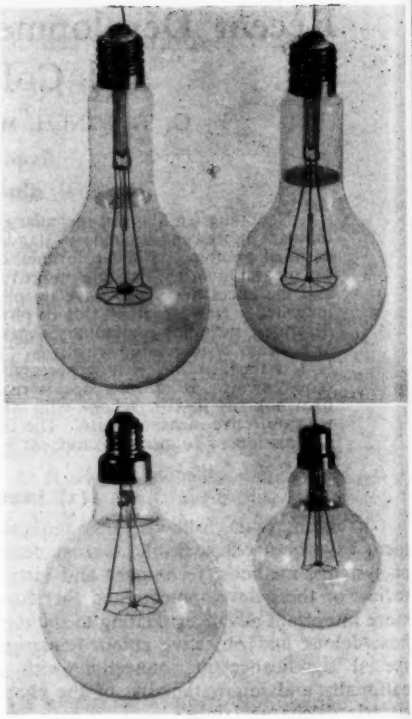

Fig. 2 (right). Examples of gas-filled secondary standard lamps.

tungsten filament secondary standard lamps of higher stability than was necessary in earlier years. In addition, a greater range of ratings is now required, including types suitable for directional intensity calibration and others suitable for calibration of total luminous flux. Included in this requirement is an increasing need for secondary standard electric discharge lamps, particularly of the tubular fluorescent types.

In view of this situation, a new range of tungsten filament secondary standard lamps which is described in more detail elsewhere[2] has recently been developed in collaboration with the National Physical Laboratory.

A design of directional intensity, vacuum, uniplanar, tungsten filament secondary standard lamp is shown in Fig. 1. In order to improve robustness, the glass frame from which the filaments are mounted has two supporting limbs to the pinch instead of one as in earlier designs. This glass frame is etched to give it a matt surface and so prevent specular reflections from the filament, which have been found to be the main cause of non-uniform intensity distribution from the lamp at small angles from the normal to the filament plane. This improvement reduces the precision of location to which it is necessary to set up the lamp for a given accuracy of directional intensity calibration, so that the use of N.P.L. pattern locating holders with these lamps is necessary only for the most precise standardisation purposes.

For use as secondary standards of luminous flux, special designs of gas-filled lamps have been developed, incorporating specially stabilised tungsten spiral filaments mounted in the form of a complete (circular) wreath and welded to the leading-in-

wires and supports. This prevents small variations of contact at supports, which can occur where a filament is mounted loosely on supporting loops, as in general lighting service lamps in which these variable contacts at supports are unimportant. The complete wreath form of filament used in these gas-filled secondary standard lamps ensures a symmetrical and fairly uniform polar distribution of light. This facilitates the determination of the total luminous flux from polar distribution measurements, and minimises errors due to imperfections of photometric integrators when such lamps are used for calibration purposes. The use of a spherical bulb with a mica baffle at the entrance to the neck minimises gas turbulence, such as can occur in a pear-shaped bulb, thus preventing momentary fluctuations of light output which can be caused by variations in cooling by the gas convection currents under turbulent conditions. Examples from the range of these gas-filled secondary standard lamps are shown in Fig. 2.

The rate of fall in light output of the secondary standard tungsten filament lamps, of the types referred to above, is of the order of 0.001 per cent. per occasion of use when the lamps are operated on D.C. Occasion of use in this sense implies operating the lamps in the photometer for about five minutes to allow them to reach thermal equilibrium before making the measurements which may occupy about another two or three minutes.

A study of the rate of fall of good quality 40-watt tubular fluorescent lamps of recent manufacture has shown that after ageing for 500 hours, they change by about 0.01 per cent. per occasion of use on A.C. Occasion of use in this case implies operating the lamp for a stabilising period of 15 minutes before making the photometric measurements, which may take up to a further two or three minutes. The rate of change mentioned above was obtained when the lamps were set up to rated watts at a stated ambient temperature and after the arc had been struck. During the photometric measurement, each pair of cathode terminals was short-circuited.

It should be noted that the rate of change of both tungsten filament and fluorescent electric discharge lamps has been quoted in relation to the occasion of use rather than to operating time. This is because in electric discharge lamps the rate of change of light output is as much dependent on the number of switchings and operating circuit conditions, as on the total operating time. By referring to the rate of change per occasion of use, it is possible to make a practical comparison between the performance of the two very different classes of lamps.

Although, as indicated above, the rate of change of these fluorescent lamps is about ten times that of tungsten filament secondary lamps, it is small enough for the fluorescent lamp to have a limited application as a secondary standard.

(3) Photometric and Colorimetric Inter-comparisons with Fluorescent Lamps

The degree of stability of fluorescent lamps, indicated in the previous section, encouraged the author to take with him to the United States in September, 1954, a batch of six such fluorescent lamps for an informal photometric and colorimetric inter-comparison. These lamps were measured in the author's laboratory by his colleagues, before and after the circulation, and the results of the measurements were not exchanged between the participating members until after the measurements and circulation were completed.

Tables 1 and 2 summarise the results obtained by the four participating laboratories, namely, Bureau of Standards, Washington; Nela Park Laboratories of the G.E. Co., Cleveland, United States; the National Physical Laboratories, Teddington, and the Research Laboratories of the G.E.C. Ltd., Wembley.

The measure of agreement indicated is of particular interest in view of discrepancies up to 10 times this magnitude, in commercial luminous flux and colorimetric measurements carried out in industrial organisations in America and Europe, reported

by Geiss at the 1954 I.E.C. meetings in Philadelphia and the 1955 C.I.E. meetings in Zurich.

(4) Visual Photometry and Colorimetry

There has been little change in recent years in visual photometric and colorimetric techniques and instruments. This is rather to be expected, as visual techniques have now largely been superseded by physical techniques, which are referred to in the later sections of this paper.

Probably the most interesting aspect of visual photometry and colorimetry is that which has arisen from recent vision studies, especially in relation to the C.I.E. 1924 and 1931 Standard Observer data. It will be remembered that the 1931 C.I.E. Standard Observer is defined in terms of three distribution functions, $\bar{x}$, $\bar{y}$ and $\bar{z}$ of which $\bar{y}$ is identical with the C.I.E. 1924 "Average Eye" spectral sensitivity or relative luminous efficiency data.

Since the C.I.E. Standard Observer was established, a number of workers have questioned the validity of the data, particularly at the ends of the spectrum and in relation to evidence of non-linear additivity of light of saturated colours. In this general connection, at the C.I.E. meetings in 1948, members of the United States delegation reported discrepancies concerning titanium off-white test samples which had led to commercial embarrassment. These specimens had, by photoelectric spectrophotometry and calculation, using the C.I.E. data, been assigned similar chromaticity values, whereas by subsequent visual inspection they appeared noticeably different in hue, and visual measurement indicated that they were different in chromaticity. Independent investigations by Judd[3], MacAdam[4], Wright[5], Ishak and Teele[6] and others, have indicated that the C.I.E. Standard Observer data undervalues the blue end of the spectrum, and it was considered that this might have a bearing on the chromaticity discrepancies referred to above.

At the C.I.E. meetings in 1955, Stiles[7] reported some particularly interesting results which he had obtained using a new form of apparatus and technique for the redetermination of the colour mixture data. His very extensive measurements over the whole of the visible spectrum by a pilot team of 10 observers, whilst not in complete agreement with the American workers' provisional results over a limited wave-length range, nevertheless showed the same general trend. Stiles is now repeating the colour mixture determinations, with a team of about 50 observers using a large field of view and if, as seems probable, the preliminary results obtained by his pilot team are confirmed, it may become necessary for the C.I.E. to consider modifying the present Standard Observer data. It appears from Stiles's new colour mixture data that modifications to the present C.I.E. $\bar{x}, \bar{y}, \bar{z}$ distribution functions could provide a system which may minimise or eliminate discrepancies between calculated chromaticity from spectral energy distribution data, and *visual colour experience* and measurement. Unfortunately, however, if such an adjustment were made, the $\bar{y}$ function derived by linear transformation from the new data would not be identical with a visual luminous efficiency curve which would be consistent with *visual heterochromatic photometric experience* and measurement. This would be particularly noticeable with light of the more saturated colours towards the ends of the spectrum. Stiles has pointed out that it might be necessary, therefore, to consider the use of a fourth function for the visual luminous efficiency curve in addition to the three of the form which at present define the Standard Observer. It may, however, prove more convenient ultimately, not to have an additional function, but to choose convenient constants for use in the calculations for deriving a $\bar{y}$ function from the colour mixture data so that for the more common light sources, such as tungsten filament and tubular fluorescent lamps, the resultant changes in photometric level would be small. For example, it would probably be most convenient to retain the present photometric level and values at, say, 2,360 deg. K., approximately the colour temperature of vacuum

Table 1

Comparison of measurements of luminous flux on 4 ft. 40-watt fluorescent lamps at 27 deg. C. carried out by National Physical Laboratory, Teddington; Bureau of Standards, Washington; Research Laboratories, The General Electric Company, Ltd., Wembley; General Electric Co., Nela Park, Cleveland.

		Measured at 23 deg. C.	Corrected to 27 deg. C.	Measured at 27 deg. C. ambient temperature							
		N.P.L.	N.P.L.*	G.E.C.–R.L.			Bureau of Standards		G.E.–Nela Park		
Lamp No.	Colour Name	Lumens	Lumens	Lumens	Diff. Col. 5 from Col. 4 per cent.		Lumens	Diff. Col. 7 from Col. 4 per cent.	Lumens	Diff. Col. 9 from Col. 4 per cent.	
1	2	3	4	5	6		7	8	9	10	
R85A54	Warm	1,940	1,959	1,954	—0.25		1,940	—0.95	1,930	—1.50	
B	White	1,930	1,949	1,951	+0.10		1,920	—1.50	1,902	—2.40	
C		1,900	1,919	1,917	—0.10		1,890	—1.50	1,898	—1.10	
	Average Difference (per cent.)			...	...	—0.08		—1.32		—1.67	
R86A54	New	2,220	2,240	2,240	0		2,220	—0.90	2,206	—1.50	
B	Warm	2,300	2,325	2,340	+0.65		2,310	—0.65	2,320	—0.20	
C	White	2,310	2,330	2,350	+0.85		2,310	—0.85	2,328	—0.10	
	Average Difference (per cent.)			...	...	+0.50		—0.80		—0.60	

*These corrected values were estimated from the N.P.L. measured values at 23 deg. C., Column 3. The correction was derived from the difference found by G.E.C.–R.L. between their measured values on these lamps at 20 deg. C. and 27 deg. C., assuming that the change was linear with temperature.

Table 2

Comparison of measurement of chromaticity on 4-ft. 40-watt fluorescent lamps carried out by National Physical Laboratory, Teddington; Bureau of Standards, Washington; Research Laboratories, The General Electric Company Ltd., Wembley; General Electric Co., Nela Park, Cleveland.

Lamp No.	Colour Name	Ambient Temperature: 20 deg. C	21 deg. C		27 deg. C		27 deg. C		20 deg. C	21 deg. C		27 deg. C		27 deg. C	
		NPL	G.E.C.–R.L.		Bureau of Stds.		G.E. Nela Par		NPL	G.E.C.–R.L.		Bureau of Stds.		G.E. Co. Nela Park	
		x	x	Diff. from N.P.L.	x	Diff. from N.P.L.	x	Diff. from N.P.L.	y	y	Diff. from N.P.L.	y	Diff. from N.P.L.	y	Diff. from N.P.L.
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
R85A54	Warm	.446	.447	+.001	.444	—.002	.437	—.009	.392	.391	—.001	.396	+.004	.386	—.006
B	White	.443	.445	+.002	.442	—.001	.435	—.010	.390	.388	—.002	.395	+.005	.383	—.007
C		.446	.448	+.002	.445	—.001	.439	—.009	.390	.389	—.001	.395	+.005	.387	—.003
Average Difference				+.0017		—.0013		—.0093			—.0013		+.0049		—.0053
*Average of above 3 lamps (Nela Park only)							.4495	+.0045						.393	+.0023
R86A54	New Warm	.442	.443	+.001	.441	—.001	.436	—.006	.504	.404	—.001	.411	+.006	.399	—.006
B	White	.441	.445	+.004	.440	—.001	.434	—.006	.404	.401	—.003	.409	+.005	.400	—.004
D		.441	.445	+.004	.440	—.001	.435	—.006	.405	.401	—.004	.410	+.005	.398	—.007
Average Difference				+.003		—.001		—.006			—.0027		+.0053		—.0057
*Average of above 3 lamps (Nela Park only)							.446	+.0047						.408	+.0033

*Alternative chromaticity coordinates calculated by G.E.C.–R.L. from G.E.–Nela Park measurements of the average spectral energy distribution curve for the three lamps of each colour.

tungsten filament lamps, or 2,850 deg. K., approximately the average colour temperature of gas-filled tungsten filament lamps, and accept the resultant level on tubular fluorescent lamps which might then make them perhaps 3 or 4 per cent. higher in lumens than at present, which would probably not cause commercial embarrassment. There would, however, be larger changes in the values assigned to light sources of some of the more saturated colours, but in most applications of such sources it is thought unlikely that the changes would be embarrassing.

It is obviously very important that careful consideration be given, by all those concerned, to repercussions likely to result from any changes of the type referred to above, which at a later date it may be thought desirable to put forward to the C.I.E. in terms of recommendations for new modified Standard Observer data.

Before concluding this section of the paper some reference should be made to visual colorimetry, particularly having in mind some of the problems which arise when attempting to carry out colorimetric measurements on tubular fluorescent electric discharge lamps by visual techniques.

The spectral energy distribution of tubular fluorescent lamps and other electric discharge lamps departs in form from that of tungsten filament lamps, which must be used for calibration purposes, and also from the resultant spectral distribution of mixtures of the primary or matching stimuli used in visual colorimeters. Consequently, because of differences in individual observers' colour vision, appreciable discrepancies may arise between different observers' chromaticity determinations. Such discrepancies are large in three-stimuli colorimeters, and it was for this reason that Donaldson[8] developed his six-stimuli instrument. This enables a nearer approach to an energy as well as a colour match to be realised and consequently reduces individual observer errors. Difficulties and errors may still arise, however, with the best of visual colorimeters, and for this reason photo-electric colorimeters as well as photometers have been developed in recent years, and these are referred to in section (5).

(5) Physical Photometry and Colorimetry

Physical photometers capable of high precision and suitable for comparing lamps having similar spectral energy distribution have been established for 25 years. Physical heterochromatic photometry did not, however, become practicable until special multi-component filters had been developed, which, used in conjunction with photo-electric cells, provided an overall spectral response fairly close to that of the C.I.E. 1924 Average Eye, i.e., the $\bar{y}$ function of the C.I.E. Standard Observer. A photo-electric photometer incorporating such a filter, in this case a Preston type "Average Eye" liquid filter, is shown in Fig. 3.

It is not possible, however, using filters in combination with photocells or other physical receptors, to achieve exactly the C.I.E. Standard Observer spectral sensitivity. Although by this means a precision of the order of 0.1 per cent. can be achieved, the absolute accuracy obtainable by this method of heterochromatic photometry is not sufficient where the highest accuracy is required, unless corrections are applied to the results. Such corrections can be determined by calculation, from a knowledge of the spectral distribution of the sources being compared and the spectral sensitivity of the photocell-filter combination used.

By using, instead of a filter, an optical dispersion system of the form indicated in Fig. 4 with an appropriate template, or mask, in the spectral image plane, a very close simulation of the Average Eye or $\bar{y}$ function of the Standard Observer can be obtained[1, 9]. In this arrangement the mask is critically shaped so that the light of the different colours throughout the spectrum is attenuated appropriately before falling on to the photocell. Not only can the $\bar{y}$ function be accurately realised in practice by this means but also that of the $\bar{x}$ and $\bar{z}$ or any other desired spectral response. With masks of the $\bar{x}, \bar{y}$, and $\bar{z}$ form mounted in a wheel as shown in Fig. 4,

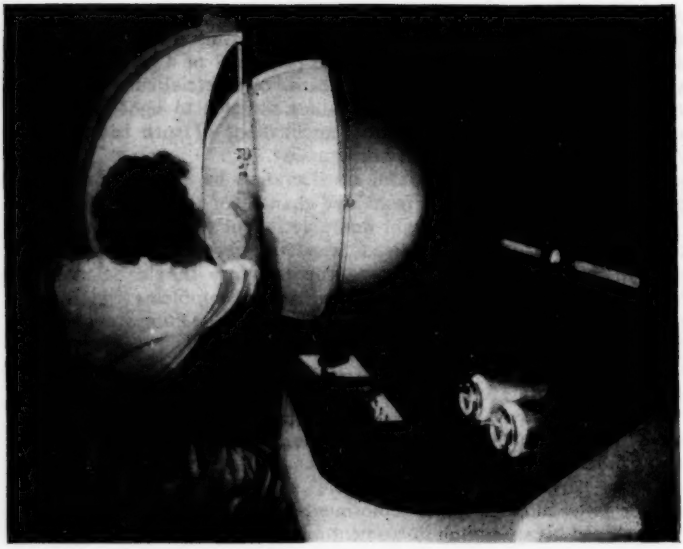

Fig. 3.
Metre sphere.

photoelectric measurements can be made in succession through each mask. The values obtained with the $\bar{y}$ mask indicate directly the light values, and together with the values obtained through the $\bar{x}$ and $\bar{z}$ mask give results directly proportional to the chromaticity co-ordinates in the C.I.E. trichromatic system. The eight other masks shown in the wheel in Fig. 4 are adjacent sections of the $\bar{y}$ shape. Through these, in turn, can be measured the luminance in eight spectral or colour band components of the light source under test. These abridged spectral luminance values, together with the chromaticity values provide an objective record of characteristics which, under one specific condition of use, are related to the colour-rendering properties of the light source measured[10]. The relationship of these objective characteristics to colour rendering under other conditions is dealt with in more detail in section 9.

A combined photometer and colorimeter operating on this principle may be used for carrying out directional measurements of intensity and colour, or together with a photometric integrator can be adapted to measure total luminous flux and average colour, also objective colour-rendering properties of light sources. Such a Physical Eye Photometer and Colorimeter[9], is shown in Fig. 5, in use in conjunction with a 12-ft. spherical integrator; this apparatus is suitable for routine use by non-technical operators. Experience with this instrument has shown that, when calibrated by reference to tungsten filament secondary standard lamps, the accuracy achieved is comparable with that at present obtained by the laborious best visual methods using several observers, or by calculation from spectral energy measurements and the C.I.E. Standard Observer data.

An example of the accuracy achieved by the physical eye photometer and colorimeter, calibrated in the manner described above, is indicated by the results contained in Tables 1 and 2, which were referred to in section (3).

The accurate methods of colorimetry mentioned above, namely indirect colorimetry by calculation from spectral energy distribution, visual colorimetry using a six stimuli colorimeter, or direct physical colorimetry by the dispersion and mask method, all involve the use of expensive apparatus. The use of such apparatus for

commercial measurements of lamp rating, etc., can seldom be justified on economic grounds and in an attempt to meet a requirement for less expensive equipment, many simpler forms of visual and photoelectric differential colorimeter have been designed. Instruments of this class usually only approximate the desired physical requirements necessary for accurate colorimetry of sources of all colours and spectral distributions. If calibrated by substitutional methods, against secondary standards of the same form of spectral distribution as those to be measured, an accuracy suitable for some commercial applications can be obtained. The main difficulty is to obtain suitable secondary standard lamps calibrated to the requisite accuracy although, as indicated in section (2), this is now becoming more practicable. One experimental instrument in this class has been recently developed by B. M. Young[11].

This instrument incorporates a selenium photovoltaic cell and three filters providing, in turn, spectral responses approximating to the C.I.E. Standard Observer data. A special circuit arrangement eliminates the need for calculation and the chromaticity values are indicated directly on a specially scaled meter.

(6) Photometry and Colorimetry by Radiometry

In recent years great advances have been made in radiometric techniques and it is probable that in the foreseeable future an accuracy and speed of measurement may be achieved which may be found useful in indirect photometry and colorimetry in the standardising laboratory. Should this ultimately prove to be the case, there may then no longer be the need for the present primary standard of light, with the attendant photometric difficulties of transferring the unit from the primary standard to other sources very different in colour and spectral distribution.

The spectral energy distribution of a light source would be determined in watts radiated per unit solid angle throughout the visible spectrum, and from such radiation measurements photometric and colorimetric values would be derived by calculation, using the C.I.E. Standard Observer data and the mechanical equivalent of light.

As has been indicated earlier, one of the great difficulties in applying the above technique would be that of obtaining sufficient sensitivity, as high accuracy is required and accuracy would be dependent on sensitivity.

(7) Improved Sensitivity and Accuracy

(7.1) Photomultiplier and D.C. Amplifier

In view of the limitations imposed by inadequate sensitivity in the applications described in Sections 5 and 6, considerable thought has been given to ways of increasing

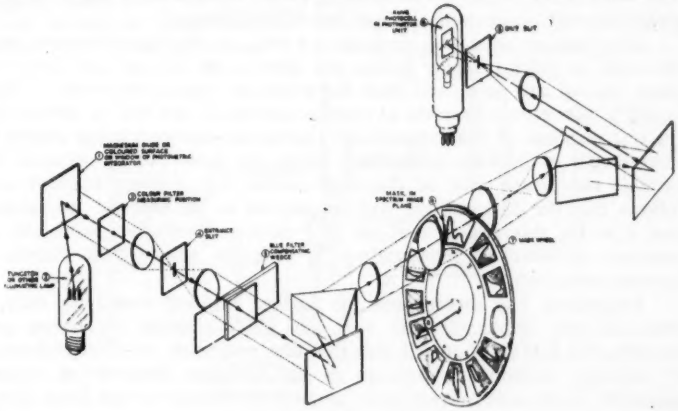

Fig. 4. Optical system of physical eye.

Fig. 5 Physical eye and 12ft sphere.

sensitivity and consequently accuracy, also of possible speed of measurement. In this section, therefore, a method of increasing accuracy is considered.

The sensitivity of photoelectric methods of measurement is determined by the limiting sensitivity of the photocell and absorption of the necessary associated filters or other essential apparatus. There is confusion sometimes between the sensitivity of a photocell in terms of micro-amperes per lumen and its limiting sensitivity. The latter is the important controlling factor when considering the ultimate attainable sensitivity and when using the best amplifying means.

The limiting sensitivity depends not only on the micro-amperes per lumen of the photocell or other receptor device, but also on the leakage and dark current, as these latter control the noise and thus the minimum signal detectable. The dark current is due to thermionic emission at room temperature and will be related to the form and spectral response of the cathode, the thermionic emission being greater the longer the wave-length of limiting sensitivity. Thus, the more red or infra-red sensitive is the cathode the greater will be the dark current for a given ambient temperature. It follows that the dark current will be reduced as the ambient temperature is reduced, and it is for this reason that red and infra-red sensitive photocells are sometimes operated at liquid air temperatures in order to reduce dark current and therefore increase sensitivity.

Experience has shown that the highest limiting sensitivity may sometimes be obtained from photocells with very low micro-amperes per lumen sensitivity. For example, the KMV6 photocell with thin film potassium on silver-cathode, which is used in precision photometry because of its accurate linearity of response[1], has a sensitivity of the order of two micro-amperes per lumen to light from a tungsten filament

lamp operating at 2,700 deg. K. Its dark current, however, is less than 10^{-13} ampere at 20 deg. C. and consequently this cell can be used successfully with a 10^{12} ohms grid leak in a D.C. amplifier incorporating a miniature electrometer triode which has a grid insulation $>10^{14}\Omega$. In this arrangement the minimum detectable signal is about 10^{-10} lumen. This is about the highest sensitivity obtainable using single stage photocells.

In attempts to increase sensitivity and consequently accuracy in photometric and colorimetric measurements, photomultiplier photocells have very naturally been considered. For some years photomultiplier cells have been available with sensitivities of up to 20 amps per lumen but, because of their high dark currents, their limiting sensitivity has often not been better than that obtained when using a KMV6 cell and a D.C. amplifier.

Also, the spectral response of cathodes of available photomultipliers was often not suitable for correction to the Standard Observer curve. Again, there has been very little knowledge of the departure from linearity of response of photomultipliers over the range of illumination involved in precise photometric and colorimetric applications.

In 1947 Engstrom[12] published comprehensive data relating to R.C.A. photomultipliers, including types with cæsium-bisbuth cathodes having a spectral sensitivity which could be corrected for heterochromatic photometry purposes. Low dark currents were quoted and the linearity of response of the output was claimed to be within the experimental accuracy of 3 per cent. in the range of anode current of 10^{-9} to 10^{-3} amp. This corresponds approximately to light levels of about 10^{-10} to 10^{-4} lumen. It seemed likely, therefore, that these photomultipliers might be a means of achieving greater photometric sensitivity and experiments have been carried out to this end.

An R.C.A. photomultiplier cell, development type C7138, has been used, together with a miniature electrometer triode in the d.c. valve bridge circuit shown in Fig. 6. Preliminary measurements of linearity have shown that within the accuracy of the method of measurement used, namely about 2 per cent., the output of this photomultiplier is linear over a 12 to 1 light ratio at a level of 10^{-9} lumen. It is hoped later to make more precise measurements of linearity using the summation of light method.

It is still questionable whether the photomultipliers referred to above would be suitable for applications in the dispersion and mask technique referred to in Section 4, where the linearity of the photocell has to be relied on to integrate the light coming through the mask. This requires linearity of response to a very high order of accuracy, comparable with that of the KMV6 cells used at present, which is a few parts in 10,000 over a light ratio of 10 to 1.

The minimum detectable signal obtained with the photomultiplier in the circuit of Fig. 6 was about 10^{-11} lumen at 20 deg. C., but with liquid air cooling this could be

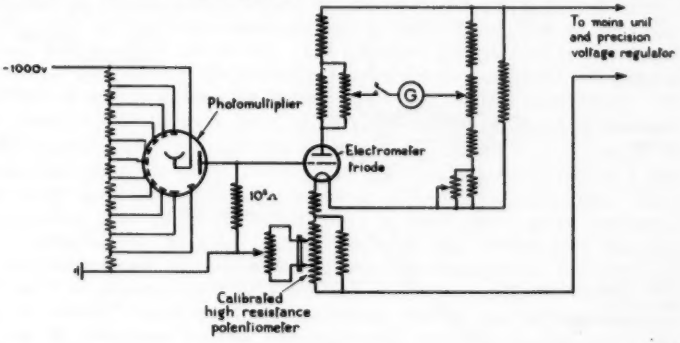

Fig. 6. Circuit diagram of photomultiplier.

reduced to 10^{-13} lumen. This is from a hundred to a thousand times higher sensitivity than that achieved with the KMV6 single stage cell and D.C. amplifier. Another advantage of using a photomultiplier is that the time constant is much shorter than that of the KMV6 cell and D.C. amplifier combination, in which a high grid leak of 10^{12} ohms is necessary.

(7.2) Photomultipliers and Photon Counting

In Engstrom's paper, referred to in Section 7.1, a minimum detectable signal of 10^{-16} lumen was claimed, using an R.C.A. type IP 21 type photomultiplier at liquid air temperature (−183 deg. C.) and an electron counting technique. Due to photons, i.e., the quanta of visible radiation incident on the cathode, electrons are released. These electrons may be counted as a means of measuring small amounts of light and this electron counting technique was used in 1948 by Yates[13] in stellar photometry. This appeared to be a promising way of achieving a much higher sensitivity than had previously been obtained by the author and his colleagues. It will be evident that this electron counting technique can only be used when the primary photocurrent is very small, such as occurs below about 10^{-10} lumen. At or below this low light level the primary cathode current to be measured is in the region of 10^{-15} amp or less, so that the number of electrons being emitted from the cathode is about 10^4 or less per second. When an electron is released from the cathode of a photomultiplier the subsequent multiplying stages produce a burst of electrons at the anode, this process taking less than 10^{-8} second. The resulting voltage pulse at the anode can be amplified in a pulse amplifier and counted by an electronic counter, and this provides a convenient means of counting the individual electrons from the primary cathode.

In order, therefore, to investigate the practicability of electron counting techniques in photometric and colorimetric applications, a unit was made up incorporating an R.C.A. photomultiplier cell type C7138, having a transparent end cathode so mounted

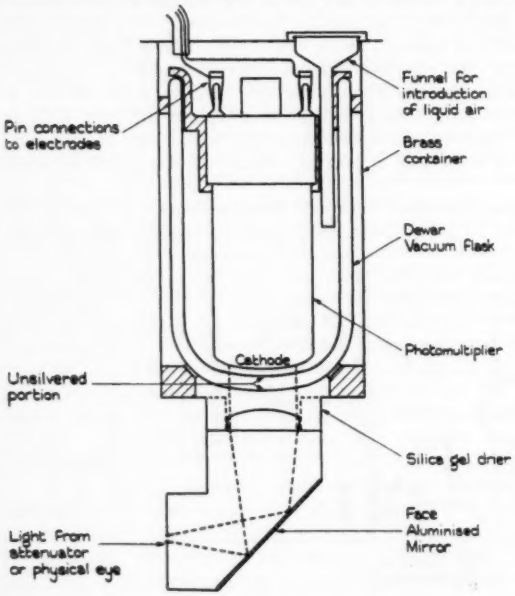

Fig. 7. Cooling unit for photomultiplier.

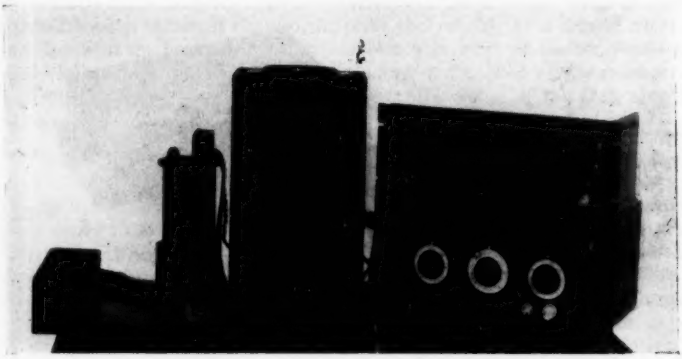

Fig. 8. Multiplier housing coupled with pulse amplifier and electronic counter.

in a Dewar vacuum flask that the cathode of the photocell could be immersed in liquid air. A small area at the bottom of the flask was left unsilvered to allow the light to fall on the cathode of the photomultiplier. The whole unit was made of dimensions such that it could be inserted in a Physical Eye Colorimeter, in place of the existing housing containing the photometer unit incorporating a KMV6 single-stage photocell. A section drawing of the liquid air cooled photomultiplier unit is shown in Fig. 7, and a photograph of the multiplier housing coupled with the pulse amplifier and electronic counter for electron counting purposes is shown in Fig. 8.

It was necessary to devise a means of providing known ratios of luminous flux at very low levels, in order to carry out tests on the sensitivity and approximate linearity of response of the photomultiplier unit used with the counting circuit, so that its performance could be compared with that of the existing photo-electric photometer unit. A special form of neutral light-attenuator was therefore designed, a photograph of which is shown in Fig. 9, and a cross sectional drawing in Fig. 10.

An extensive programme of investigations is at present in hand with the equipment referred to above, and it is hoped at a later date to publish results of this work in detail.

The results of preliminary measurements indicate that the limiting light sensitivity achieved by the electron counting technique with the present apparatus is probably at least a thousand times higher than that achieved earlier with the KMV6 photocell photometer unit in a d.c. valve bridge amplifier. There appear likely, however, to be limitations to the use of the electron counting technique which are indicated below. At the lower light levels at which this technique will be used, the number of electrons released per second will be about 10^4 or less. The electrons are released at a random rate so that, when they are counted, the final accuracy of the measurement will depend on the total number of counts made. By Poisson's law for random distribution, the error in a single count of n electrons is given by $n^{\frac{1}{2}}$. If, for example, the total number of counts is 10,000 electrons then the probable error will be $\sqrt{10{,}000}$, i.e., 100, which is 1 per cent. of the total count. In order, therefore, to limit the probable error to 1 per cent. in a single set of counts it is necessary to count at least 10,000 electrons. This clearly controls the time over which the count must be made for a given accuracy. A further limit is imposed at the other end of the scale due to the fact that the maximum rate of counting will be dependent on the time constant of the counting circuits. The counter at present being used will not count more than 10^6 pulses per second. It will be evident, therefore, that the current due to the highest intensity of light which can be measured by this technique will, with the counter used, be

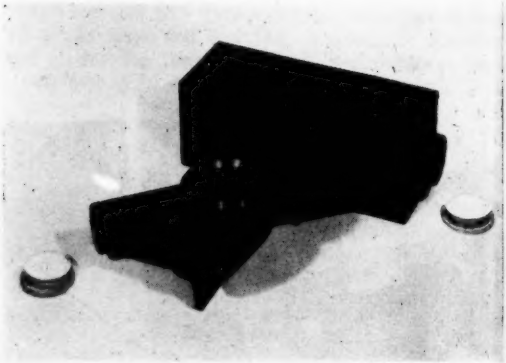

Fig. 9. Neutral light-attenuator.

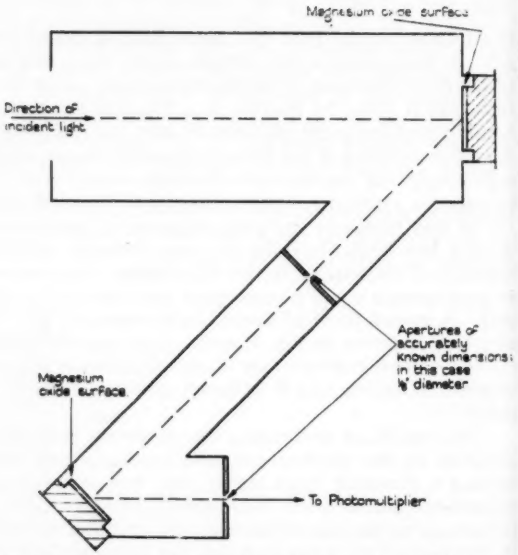
Magnesium oxide surface
Direction of incident light
Apertures of accurately known dimensions: in this case ¼" diameter
Magnesium oxide surface
To Photomultiplier

Fig. 10. Sectional drawing of light-attenuator.

limited by the situation where 10^6 electrons are being released from the cathode per second, corresponding to about 10^{-9} lumen. At higher intensities, the counter would not resolve the individual pulses due to the electrons and consequently the count would no longer be linearly related to the cathode current produced by the incident light. As indicated earlier in this section, accurate measurements of linearity using the electron counting technique have not yet been completed, but it is hoped to carry out such measurements using the summation of light method.

From the present provisional results it would seem that the electron counting technique may prove useful as a means of achieving greater sensitivity and accuracy. If the present experiments in applying this technique in the Physical Eye Photometer and Colorimeter are successful, an overall increase in accuracy of photometry and colorimetry, etc., by the dispersion and mask method should result. Another very attractive feature of the electron counting technique is that the count will be indicated

in numbers on the counter. By the addition to the counter circuit of a relay mechanism it should be possible, if desired, to print the results on a record sheet. This facility, coupled with the rate at which the necessary number of counts would be made, seems likely to result in a considerable shortening of the time of the measurement operation as compared with that at present experienced when using the D.C. amplifier techniques, particularly at the lower light levels.

(8) Paint for Photometric Integrators

In the past, zinc oxide and other white matt paints used in photometric integrators have proved satisfactory for photometric purposes. Although these paints show small departures from neutrality, no serious photometric errors have arisen in consequence. Buckley[14] showed that the departures from neutrality were unlikely to introduce errors when measuring tungsten filament lamps, but that when measuring line spectra sources, such as sodium and mercury lamps, errors up to 1 or 2 per cent. might occur, using an integrator calibrated by reference to tungsten filament lamps. Where a higher accuracy is required, it is not difficult, however, to calculate the corrections which must be applied. The development of accurate physical simulations of the Standard Observer used for the measurements of the average chromaticity of light sources when operating in photometric integrators has, however, introduced a much more stringent requirement for integrator paints. Whereas, as has already been indicated, the photometric errors are comparatively small and can be calculated and corrected for, the errors in chromaticity from the same cause can be large. As indicated earlier[1, 9], the mask shape in the Physical Eye Colorimeter can be determined and made to compensate for the departure from neutrality of the integrator paint. Instruments so calibrated eliminate errors from this cause, provided the paint does not change. Earlier forms of integrator paint such as zinc oxide, etc., change their spectral reflection factor with age, so that even where mask shapes have been adjusted to compensate for paint imperfections, errors will arise with the passage of time, due to changes in the paint characteristics. To a large extent compensation can be made for such changes in paint spectral reflection characteristics by the use of a wedge type adjustable temperature conversion filter, such as is incorporated in the Physical Eye Photometer and Colorimeter[9]. It is very desirable, however, to seek a paint which is as neutral as possible, but even more importantly, one which will remain constant in its spectral reflection characteristics.

Middleton[15] has proposed the use of barium sulphate paint for integrators with carboxy-methyl-cellulose (CMC) as binder, but the proportions were such that an adherent coating could not be produced, and when applied was too fragile for constant handling. Further experiments were therefore directed towards increasing the proportion of binder so that the paint would be suitable for commercial applications. Preliminary results have shown that with an improved binder ratio of 5 per cent. the barium sulphate paint can be made to specification and reproduced more uniformly; it is also more stable than earlier forms of paint.

Measurements of the reflection characteristics and fluorescence of barium sulphate pigment have shown it to be greatly superior to zinc oxide in that the barium sulphate has a fairly uniform spectral reflection in the visible region and a very high U.V. reflection factor, although no measurable fluorescence.

Investigations are continuing into the problem of suitable integrator paint and one of the spheres in daily use in the author's laboratory has recently been coated with barium sulphate paint. Daily records are being kept of its characteristics so that, after an extended period of use, its performance may be compared with that of other paints formerly used in this application. In this connection, for purposes of comparison it may be useful to record the magnitude of chromaticity changes experienced with one of the earlier types of integrator paint. After three months' daily use in an

integrator, changes of the order of .02 in chromaticity from the original calibration have been recorded for paint consisting of several undercoats of Coverine and one or more coats of zinc oxide as a finishing surface.

(9) Colour-Rendering: Objective and Subjective

Reference has been made in section (5) to colorimetry and objective measurements related to colour-rendering. As colour-rendering is a subjective effect it is necessary here to make brief reference to the studies which have been made in this connection, in an attempt to relate *subjective colour-rendering* with *objective measurements*.

It has been shown ([10, 16]) that the colours of objects as seen by any one observer are dependent on the spectral energy distribution, intensity and direction of the light incident on and reflected from objects, their relative position and angular subtense at the eye of the observer and also the conditioning of the observer before and during observations. Objects having the same spectral reflection characteristics will therefore appear the same in colour to any one observer appropriately conditioned, provided the illuminating and viewing conditions are identical and the light from the illuminants has the same spectral energy distribution.

It follows, therefore, that although colour-rendering is *subjective*, in an *objective* sense the colour-rendering properties of light sources may be defined by reference to their spectral energy distribution. This class of measurement has already been referred to in section (5).

In order to ensure uniformity of lamp colour-rendering characteristics it is obviously sufficient to specify the *objective* colour-rendering properties. The objective method of measuring colour-rendering properties by reference to luminance in eight spectral bands, which is, of course, a form of abridged spectrophotometry, indicates the approximate spectral luminance distribution of the source. Such values, if coupled with the chromaticity, will indicate, within commercial limits, the class of colour-rendering of the lamp being measured.

Concerning the spectral band intervals used in the objective measurements, it is thought that the present wave-length intervals could perhaps be modified with advantage, but so far no very satisfactory modified recommendations have been made. Many different sets of wave-length intervals have been proposed in the past, and it seems likely that if any change is made it should probably be based on spectral radiation data combined with a weighting factor which might, for example, be the root mean square of the three distribution curves of an approximately uniform chromaticity system linearly related to the C.I.E. system.

(10) Future Developments

It has been shown that in recent years considerable progress has been made in photometric and colorimetric techniques and instruments. It seems likely that one of the most interesting lines of investigation for improving the accuracy and speed of photometric and colorimetric measurements will be in the field of electron counting, mentioned in Section 7.2, and this work is continuing.

It is interesting to speculate on other possible lines of investigation which might prove fruitful. One such possibility is the application of an effect described earlier by Debye and Sears([17]), Bergmann([18]), and recently referred to by Rosenthal([19]). These workers show that ultrasonic waves in a transparent medium can act upon light in a way similar to a diffraction grating. In order to achieve this, the ultrasonic wave fronts must be parallel to the direction of the transmitted light. Such an ultrasonic wave grating may be used as a monochromator, the wave-length being dependent on the frequency and the transmission on the amplitude of the ultrasonic waves.

This technique might conceivably be applied to certain aspects of photometry and colorimetry, as it provides a narrow pass filter the wave-length interval of which can

be controlled electronically at high scanning speeds. This might enable almost instantaneous measurements to be made of relative spectral distributions, in connection with objective colour-rendering measurements and might conceivably be applied in physical colorimetry. The attraction of the method would seem to be the rapid rate of scanning without the use of normal types of filter or dispersion systems.

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Discussion

DR. J. W. T. WALSH: The first part of the paper which interests me specially is, not unnaturally, that dealing with the secondary standard lamps developed in collaboration with the N.P.L. The etching of the glass supports is an ingenious device for reducing the effect of reflections from the internal structure, but I should like to ask whether Mr. Winch has made any trials with the tilted inverted-cone form of bulb designed to avoid trouble due to reflections in the rear surface.

Next I should like to refer to the results of the inter-comparison as detailed in Table 1. It is interesting to notice that the differences between the laboratories in either country are much less than the overall spread of the values. This is not surprising, but it seems to indicate a need for further inter-comparisons between the N.P.L. and the N.B.S.

Probably the most controversial part of the paper is that dealing with the relationship between the colorimetric observer data and the luminous efficiency of radiation, as found by ordinary photometric methods. It has always seemed to me that it is useless, or rather meaningless, to attempt to determine such data with high precision, because they are so dependent on the conditions under which observations are made. What is needed for practical purposes is a convention which will not conflict with ordinary everyday experience, and I feel strongly that it should be possible to arrive at such a convention, applicable to both photometry and colorimetry.

With regard to the diagram of the "attenuator" which Mr. Winch showed on the screen, I should like to ask whether the factor of attenuation is determined experi-

mentally or calculated from the dimensions of the apparatus. If the latter, it seems to me essential that, for *every* point on each diffusing surface, the aperture which illuminates it should be completely filled by the immediately preceding diffusing surface and it was not clear in the diagram that this condition was always fulfilled.

I cannot conclude without paying a most sincere tribute to Mr. Winch's work in the allied fields of photometry and colorimetry. The progress which has been made during the last two or three decades, not only in precision but also in convenience, has been largely due to the development of photoelectric methods and in this Mr. Winch has played a very prominent part. Everyone interested in photometry and colorimetry, and that means every lighting engineer since these measurements are at the base of all lighting practice, owes Mr. Winch a debt of gratitude for the work he has done in the past and which, it is pleasant to note from the present paper, he is still actively pursuing.

PROF. W. D. WRIGHT: I think one of the most important things that needs to be said about modern photometry is that it is in a very sad state of health, in spite of the stimulating and robust-looking film that we have just seen. Unfortunately, colorimetry appears to have caught the infection, which has its main focus in the failure of additivity in heterochromatic photometry when comparing saturated and unsaturated colours. A very brief reference has been made to this by Mr. Winch in Section (4) of his paper, but I doubt whether he has said enough to illustrate the crisis that appears to lie ahead.

In America, discrepancies of as much as 30 per cent. are being widely publicised as the magnitude of the errors in photometric additivity and, by implications, errors of the same order are suggested for the additivity of colour equations. I was therefore sorry to see the sentence in Mr. Winch's paper referring to non-linear photometry, followed immediately by sentences referring to colorimetric discrepancies on titanium white samples. In fact, the evidence for the latter discrepancies is far from convincing, and in any case is of a very much smaller magnitude than that suggested for heterochromatic photometry.

It remains to be seen whether the attacks on orthodox photometry and colorimetry are sufficient to bring the subject into serious disrepute. I myself feel that the concepts of photometry are in need of some overhaul, whereas colorimetry is on a much firmer foundation, but I should be interested to know whether Mr. Winch is satisfied that photometry as a science can survive the mauling of the V_λ curve that was suggested at the 1955 C.I.E. meeting.

I was surprised to note that Mr. Winch envisages the possible abandonment of the primary standard of light. I wonder what the views of the N.P.L. are on this subject! Since there is a closed circuit between the primary standard, the energy radiated by the standard, the V_λ curve, the luminous efficiency of monochromatic radiation and the lumen, a very ambiguous situation might arise if the standard source were replaced by a radiation measurement in terms of watts. Thus if at some subsequent date, a revision of the V_λ curve were found necessary, this might lead to a change in the luminous efficiency of monochromatic radiation (the mechanical equivalent of light) and hence of the unit of luminous flux, the lumen.

Perhaps the most exciting part of Mr. Winch's paper is his description of his photon counting experiments. Since reading this, I have already in my mind designed a recording spectrophotometer in which a photometric control would be used to bring the number of photons down to a fixed number. In this way the question of linearity would be unimportant, but a number of other questions do arise. Am I right, for example, in assuming that there would be an optimum current to give the greatest accuracy? How stable is the photon counter? Would the accuracy for a given number of counts be greater if a small current were measured for a long time rather than a bigger current for a shorter time? If Mr. Winch can design a counting unit

which behaves as well as his Precision Photometer Unit, I shall be one of his first customers.

MR. D. T. WAIGH: I would like to ask Mr. Winch if he is satisfied with the application of a temperature correction to 4-ft. 40-watt fluorescent lamps mentioned in the footnote to Table 2, in view of his recommendation in another document that no correction need be applied to lumen measurements on these lamps in the temperature range 20—27 deg. C. If this correction is not applied, the agreement between the sets of measurements is not nearly as good.

I find it difficult to reconcile the figures in Table 1 with the author's claim that the agreement found on the cross-check conducted by him was 10 times better than that found in the I.E.C. cross-check. For example, the disagreement between the National Bureau of Standards and the American G.E. Co. amounts to .008 x and .0102 y and if these figures were multiplied by 10, the different measurements would represent very different colours.

In the same table, very different results are quoted for two methods conducted by the American G.E. Co. Would Mr. Winch please say what methods were used and explain why the results were so different.

In the penultimate paragraph of Section 2, it is stated that the lumen depreciation of discharge lamps is as much dependent on the number of switchings as on the burning time. This is certainly not in accordance with my experience and I should be glad if Mr. Winch would explain his statement.

DR. W. S. STILES: Mr. Winch has been kind enough to mention the collaboration of the National Physical Laboratory in the development of improved filament lamps for secondary standards. I need hardly stress that the actual lamp making, with all its difficulties, was entirely the work of the General Electric Company. There is one advantage of the new designs worth adding to those mentioned by Mr. Winch. In the new intensity standards, the absence of a central column of glass behind the filament system means that the images of the filaments reflected in the lamp bulb and located near the actual filaments are unobstructed. We found that in some older lamps the variations in occultation of these filament images by a central support column was the biggest source of variation of intensity with small changes in direction of view.

We are all aware that from a manufacturer's standpoint the production of improved standard lamps is not a paying line. But the availability of the best possible standards is important for the whole lighting industry. When, many years ago, at the request of the N.P.L., the Electric Lamp Manufacturers' Association arranged for a particular manufacturer—the General Electric Co.—to give special attention to standard lamps, a good step forward was made, and this latest work is a continuation of the arrangement. Mr. Winch will not mind my mentioning a point we have discussed privately, namely that for each improved type of standard lamp made available, a simple user's description and specification should be issued so that the purchaser knows in advance the kind of performance—rate of change with hours of burning, constancy with small variations of direction of view (intensity standards), etc.—that he may expect to get, and to which the National Physical Laboratory can refer when making calibrations.

The possibility of some change in the standard relative luminous efficiency function V_λ has been explained by Mr. Winch. What is being explored now is the practicability of starting with direct determinations of the so-called distribution coefficients of colorimetry which are used in defining the colour co-ordinates of a light stimulus. The V_λ curve is then defined as a weighted sum of the distribution coefficients. Direct determinations of these coefficients are now in progress, and it appears questionable whether a weighted sum of the results will coincide with a V_λ curve determined by some accepted method of heterochromatic photometry. The reasons for this difference

are not yet clear. Another complication is that colorimetrists may prefer to adopt distribution coefficients measured in a large colour-matching field rather than in the 2 deg. field which has previously been standard for photometry. The yellow retinal pigment is less effective in the larger field and this affects the results in the blue end of the spectrum. The upshot is that if a weighted sum of directly determined large field distribution coefficients were proposed to replace the present V_λ curve, it would almost certainly differ materially from the present V_λ curve in the short-wave part of the spectrum, below 500mμ say. As Mr. Winch points out, the effect of the changes mooted, on the relative luminous outputs of most ordinary near-white light sources, would be small. However, many photometrists and illuminating engineers may feel that there is something artificial in building up a V_λ curve in this way. To this it may be opposed that the present V_λ curve is also a conventional one and a good many observations of the relative brightnesses of sources of widely different colour are not in good accord with it. When the colour measurements now being made are completed and thoroughly analysed and tested in field trials, it may after all be decided by the C.I.E. to retain the present distribution coefficients appropriate to a 2 deg. field with perhaps a minor modification in the extreme blue. In case a more radical change should be made, it seems a very good thing to ventilate the problem as Mr. Winch has done.

The progress made on photon-counting methods by Mr. Winch is of special interest to us at the N.P.L., as the late Mr. Harding had been exploring the same field shortly before his death. He was very concerned with establishing the relationship between the number of photoelectrons emitted by the cathode of the photomultiplier and the number of pulses he succeeded in counting. I should be interested to know from Mr. Winch about the value for this ratio which would apply under his conditions.

MR. M. G. CLARKE: I would like to ask the author if he considers that radiometric techniques will be likely to supersede photoelectric methods, as severe problems will be encountered in finding adequate filters or filter systems to reduce the very wide band response of radiometric receivers to the required narrow visual band.

I also would like to know if the light attenuator mentioned in Section 7.2 has been designed to give a mathematically calculable attenuation factor and, if so, how nearly this has been found to have been achieved.

MR. G. E. V. LAMBERT: I should like to ask Mr. Winch if he could tell us more about the methods used to obtain the results quoted in Table 2. He has mentioned this evening that the dispersion and spectrum mask colorimeter was used at the G.E.C. Research Laboratories; could he also say what methods were used at the G.E. Co., Nela Park and at the National Bureau of Standards? This information would help in appraising the results and it might, for example, explain the large discrepancies between the two sets of results from Nela Park, already referred to by Mr. Waigh.

As regards the N.P.L. results, these were obtained on a Donaldson visual colorimeter with six matching stimuli. I do not think that I shall spoil the overall picture if I mention that experiments at the N.P.L. have shown that the results of chromaticity measurements on fluorescent lamps by this method may differ from those computed from the spectral distribution of power by up to twice MacAdam's standard deviation of colour matching in a 2 deg. viewing field. For the white types of lamp the discrepancy is generally found to correspond to larger values of x and y by direct colour matching. The reason for this, however, is uncertain.

Dr. Walsh has remarked, in regard to Table 1, on the way in which the two laboratories from the same country tended to agree with each other in measuring the luminous flux. The chromaticity results, however, seem to show that, in this respect, there was better agreement between the two British laboratories than between the

Americans, and it is perhaps encouraging to note also that the N.P.L. results come between those of the other British laboratory (G.E.C.) and the National Bureau of Standards.

MR. A. W. TARRANT: I would like to hear Mr. Winch's views on three points. The first two concern the use of fluorescent tubes as photometric and colorimetric sub-standards in commercial laboratories. Would it not be advantageous to have special fluorescent lamps made for this purpose instead of relying on lamps selected from the production line? Some lamps which have been sent to the N.P.L. recently for calibration were of poor quality, and for some tests, such as spectral energy distribution where only a small area of the tube is used, small defects can be serious. If special tubes of superior quality were available, I think that many commercial photometric laboratories might be able to increase their accuracy.

My second point concerns the method of running fluorescent lamps as sub-standards—namely with the filaments short circuited. When this is done the filament operates at a much lower temperature than it was designed to, and it seems to me that this must have an adverse effect on the life of the lamp, and consequently on its reliability as a sub-standard.

The third point is about D.C. amplifiers. Mr. Winch has discussed the electrometer triode type, but there are other types. At the N.P.L. we have been using a vibrating reed electrometer for measuring photocell currents of 10^{-10} to 10^{-13} amp. quite successfully, and so too has at least one other photometric laboratory. There is no very great advantage other than that a larger amplification can be obtained, and that automatic recording apparatus can be used.

MR. J. G. HOLMES: It is interesting that the type of photometry used in 1930 as portrayed by the first part of Mr. Winch's delightful film was of an order of accuracy for which the present difficulties are much less important. The questions of linearity and additivity, to which attention had been drawn in the discussion, were realised in a rather academic way at that time but they were not found to have any practical significance until great improvements were made in the accuracy of measurements during the late 1930s. These discrepancies in the familiar laws of photometry and colorimetry are of fundamental importance, but we have been reassured in the discussion that they are being examined in great detail and that those responsible for interpreting the results will handle them in such a way that commercial photometry and colour measurement will be improved in accuracy and consistency.

The large increases in sensitivity, of the order of 10 times or 100 times, mentioned by Mr. Winch appear to relate to the threshold sensitivity of his photoelectric devices and it is not quite clear whether this improvement is accompanied by a reduction to one-tenth or one-hundredth in the percentage errors in photometric measurements. This depends on the stability and resolving power of the electrical equipment and indicators associated with the photocells, and the present figures of accuracy seem to be of the same order as the errors in electrical measurements. I wonder whether equipment is available to take advantage of the present improvements in sensitivity at more normal levels of illumination.

DR. S. T. HENDERSON (communicated): The author's intention in Section (3) is evidently to show that high precision can be achieved in a carefully conducted experiment with one set of fluorescent lamps, but examination of the figures suggests that they are not so much better than those obtained in the 1955 I.E.C. interchange mentioned. Considering photometry first, the extreme values so far available in the I.E.C. experiment (not all have been reported) show a spread of roughly ± 5 per cent. in luminous flux for each of the three colours used, but this large figure was due in part to the fact that different lamps from the same batch were measured by different

laboratories. Internal evidence suggested that the inherent spread in the batch amounted to ± 2 or 3 per cent., and the remaining discrepancies (even for individual lamps) are not so very much greater than those in Table 1. There was, besides, clear evidence that some of the differences were due to the use of mutually inconsistent standards in different countries, and, indeed, Table 1 tends to confirm this. Mr. Winch's photometer is doubtless calibrated with an N.P.L. standard and his results should therefore agree with the N.P.L. values; Nela Park agrees with N.B.S. for a similar reason.

With regard to colorimetry, the methods of measurement for other laboratories are not stated, but the reasonable agreement with N.B.S. is certainly welcome. On the other hand, the wide discrepancy between the Nela Park values obtained by two methods, amounting to x .0138, y .0076 for Warm White, and x .0107, y .0090 for New Warm White, is not at all encouraging. These differences are of the same order as the spread of all the I.E.C. results so far known, and amount in this region of chromaticity to about six MacAdam standard deviations (or MPCD as usually interpreted). It is certainly possible without elaborate apparatus to obtain much closer agreement between different methods of colorimetry than in the case quoted, but Mr. Winch's data do imply that consistency is hard to obtain. The recent C.I.E. recommendation that photometric and colorimetric inter-comparisons should be made, deserves our active support in promoting more work of this kind.

THE AUTHOR (in reply): In reply to Dr. Walsh, I have been aware of the use of inverted conical bulbs in some secondary standard lamps and at the time of developing the improved design of lamps to which I have referred, we did consider the possibility of using conical bulbs As indicated in the paper, however, earlier troubles due to specular reflections from bulbs and supports appear to have been eliminated in our new designs of directional intensity standards, without resorting to the use of conical bulbs which are less attractive from the lamp manufacturer's point of view.

With reference to the luminous flux values of the fluorescent lamps, indicated in Table 1, I was interested in Dr. Walsh's comments on the systematic differences which are apparent between the average values in each country, and the much closer agreement between laboratories within the country. I would strongly support his suggestion concerning the desirability of further inter-comparisons between the National Physical Laboratory and the National Bureau of Standards with a view to resolving these discrepancies. It is hoped that this will, in fact, be included as part of the interchanges between all national laboratories, which presumably will be arranged when the N.I.C. Photometric Technical Committees implement the C.I.E. resolution:—

"It is recommended that National Committees of the C.I.E. be asked to carry out a photometric and colorimetric inter-comparison with the object of determining the consistency of the measurements made in different countries on Tubular Fluorescent lamps."

Concerning the design of the light attenuator, although the principle employed in the design is indicated diagrammatically in Fig. 10, this is not a scale drawing. It appears that inadvertently the small aperture is not fully filled by the directly illuminated white surface as seen from any point on the second diffusing surface, which is illuminated by the small aperture behaving as a secondary source. In the apparatus, a photograph of which is shown in Fig. 9, the apertures are, in fact, fully filled.

In reply to Professor Wright, I sincerely hope that the state of health of photometry and colorimetry will not appear to be, in practice, as his diagnosis would suggest. As I indicated, in the limited space available I could only deal briefly with the many aspects of photometry and colorimetry which are covered, and for this reason I could not elaborate on the points mentioned by Professor Wright. I did, however, refer to a few of the more important recent publications commenting on the photometric and

colorimetric discrepancies which have led the authors to suggest that the Standard Observer data should be modified. Personally, I have not felt satisfied that all the experimental work and measurements from which data and theories have been derived as evidence for changing the 1931 Standard Observer data have necessarily been carried out in a manner and to an accuracy consistent with present-day photometric and colorimetric measuring techniques. It may be that still closer co-operation between "vision theory interests" and the "application and measurement interests" might prove advantageous. I feel it to be rather ironical that, as indicated in Tables 1 and 2, measurements carried out in accordance with the 1931 Standard Observer data show such close agreement, whilst at the same time, as Professor Wright points out, publicity is being given, particularly in the United States, to apparent departures from the C.I.E. data as large as 30 per cent. in photometric additivity and also, by implication, the additivity of colour equations. This situation surely calls for a very careful appraisement of the data in question, and possibly further carefully planned measurements and observations by a large group of observers before changes would be justified to the 1931 Standard Observer data.

My reference to the future possibility of photometry and colorimetry being carried out in the standardising laboratory by reference to radiation measurements only and the abandonment of the primary standard of light assumed, of course, that any necessary changes would by then have been made to the V_λ curve and this would not be subject to any further modification.

I am interested in Professor Wright's thoughts concerning the design of a recording spectrophotometer utilising the photon counting technique, and his suggestion for overcoming possible departures from linearity by a photometric control based on a fixed number of counts. As I have indicated in the paper, it seems likely that there is an optimum photoelectric current range which would give the greatest accuracy, and provided the measurements were made within this range, comparable accuracies would be expected from a given number of counts for a small current for a long time, as for a large current for a short time, provided the method of timing is appropriately accurate.

In reply to Mr. Waigh's criticism of the temperature correction to the values in Table 2, this does not conflict, as he suggests, with views which I have recommended in connection with the fluorescent lamp specifications, as in the present instance the correction is based on actual measurements at two temperatures on the same lamp. I have deprecated the use of correction factors in lamp specifications, for in that case a general correction factor must be applied, and in fact quite large variations occur in the correction factors of individual lamps.

I am surprised that Mr. Waigh finds it difficult to reconcile the figures in Tables I and 2 with my claim that the values obtained in the I.E.C. inter-comparisons showed discrepancies up to 10 times this magnitude. An analysis of the discrepancies in the I.E.C. inter-comparison indicated a coefficient of variation for luminous flux of 2½ per cent. and a standard deviation for the chromaticity co-ordinates of .004. This indicates that once in 20 times the errors of individual lamps are greater than 5 per cent. for lumens and .008 in chromaticity.

At the time the paper was written we were making measurements to determine the effect of temperature on chromaticity. Although these measurements are still incomplete the results to date indicate that the y values at 27 deg. C. may be about 0.004 higher than at 20 deg. C., although the x value does not appear to change appreciably. If this order of correction is confirmed, then the Bureau of Standards' measurements would be in very close agreement with N.P.L. and G.E.C.-R.L. and also with the calculated Nela Park y values.

From the above comments it will be seen that in this informal interchange on

luminous flux measurements, the agreement is about 10 times better and in chromaticity about five times better than that shown in the I.E.C. inter-comparison.

The discrepancies in these tables have for convenience been referred to N.P.L. values. If the same technique is used as in the I.E.C. inter-comparison and the discrepancies are referred to the mean obtained by all measuring laboratories, the agreement appears very encouraging particularly if the chromaticity value for the G.E. Nela Park is taken as that derived from the spectral distribution measurements. It would seem that the larger discrepancies in the directly measured chromaticity values of G.E. Nela Park are probably associated with the fact that these measurements were carried out with a Barnes Colorimeter, in which accuracy is very dependent on pure substitutional calibration, which was probably not possible in this case.

I am sorry if I have given the wrong impression in stating that the rate of change of light output is as much dependent on the number of switchings and the operating circuit conditions as on the total operating time. Perhaps I should have said that it is not only dependent on the total operating time but also on the number of switchings and the operating circuit conditions. The important thing is that the tests for stability of the fluorescent reference lamps were carried out under conditions identical with those obtaining in the photometer and included the circuit and switching conditions as well as the time of operation.

With regard to Dr. Stiles's comments on the tungsten filament secondary standard lamps, I am glad to know that there are additional advantages as well as those I mention in the new design of directional intensity secondary standard lamps. I am in agreement with Dr. Stiles's desire for a simple user's description and specification of these various ratings of secondary standard lamps, and I hope that this may be found possible in the near future.

The more detailed comments concerning the difficulties associated with the discrepancies which have been found with respect to the Standard Observer data are most helpful, and I am interested to note that Dr. Stiles thinks that it may after all be decided by the C.I.E. to retain the present distribution coefficients appropriate to a 2 deg. field with perhaps a minor modification in the extreme blue.

As indicated in the paper, we are only in the early stages of our exploratory work on the photon counting techniques and we have not yet accumulated sufficient data on the relationship between the number of photon counts emitted from the cathode of the photomultiplier and the number of pulses counted to enable me to answer Dr. Stiles's query in this connection.

I agree with Mr. Clarke that severe problems will be encountered in radiometric techniques, but I believe that these problems are well understood by those specialising in this class of measurement. I have gathered that considerable progress has been made in this field of measurement, and that sensitivities and accuracies are steadily improving to an extent which shows future promise in the class of measurement to which I have referred.

The light attenuator mentioned in Section 7.2 was not designed to give a mathematically calculable attenuation factor to a very high degree of accuracy. The main requirement was to provide the equivalent of a strictly neutral filter of very high attenuation. This, in fact, has been achieved and the accuracy of the calculated attenuation factor is, of course, dependent on the reflection factor of the magnesium oxide surface, which is probably known to about 1 per cent., and the dimensions of the small apertures. The device has the advantage that it provides a sensibly neutral attenuator, the equivalent density of which can be calculated to within a few per cent. This accuracy was sufficient for the investigation in question as it was only necessary to know approximately the attenuation so that comparison could be made of the sensitivity of the single stage photocells in the d.c. circuit as compared with photomultiplier cells using the photon counting technique.

Mr. Lambert has asked for more information relative to the methods used for

obtaining the results quoted in Table 2. I was given to understand that at the Bureau of Standards the colorimetric measurements were carried out by a special visual technique. A series of colour filters of known spectral transmission were used in front of a tungsten filament source and by trial and error the filter found which would give the best colour match with the fluorescent lamp. From the known colour temperature of the tungsten filament lamp and the spectral transmission characteristics of the filter, the chromaticity of the transmitted light which matched that from the fluorescent lamp was calculated.

At the G.E. Nela Park, the direct chromaticity measurements were determined using a Barnes Colorimeter calibrated in substitution by fluorescent lamps used as secondary standards. They were handicapped to some extent in measuring the lamps in question in that they had no reference lamps of similar colour name and spectral distribution. They, therefore, expected that there might be some error arising because they were unable to use pure substitutional methods of calibration. It was for this reason that they also measured the spectral distribution of the lamps, from which the chromaticity could be calculated.

The statement with regard to the method of measurement used at the N.P.L. is very interesting and useful in judging the overall value of the results of this informal comparison.

I would say in reply to Mr. Tarrant's questions that the possibility of preparing special fluorescent lamps for use as secondary standards was considered at the 1948 and 1951 C.I.E. meetings. There are practical difficulties, however, in achieving this as not only are the lamps likely to be costly and of limited availability but they may be of a different geometrical form. Up to the present, it would appear that the possible small gain in stability which might be achieved would probably be offset by the introduction of errors of the same magnitude, due to the different geometrical form and polar distribution and the limitations of the photometric integrators in which the lamps would be used. Mr. Tarrant appears to have been unfortunate in having received poor quality lamps for calibration, but he will remember that in the paper I did stress that the lamps which had shown the high degree of stability were of current manufacture and good quality.

Results of measurements have shown that the technique of short circuiting the filaments of fluorescent lamps gives an improvement in repetition accuracy, and when operated in this condition it is shown that the number of occasions of use and the small rate of change makes the lamp suitable as a secondary standard, at least in a limited sense. It is improbable that a much better performance would be obtained in this application if the filaments were not short circuited during measurement.

I am interested to hear of the successful use at the N.P.L. of vibrating reed electrometers for measuring photocell currents. So far we have not used this type of amplifier in our laboratories in connection with photoelectric photometry and colorimetry, although it has been used in other applications.

Mr. Holmes's comments on the discrepancies in photometry and colorimetry and questions of linearity are interesting.

The increase in sensitivity attained by the photon counting technique may influence accuracy in more than one way, and it does not follow that the increase in accuracy will be of the same order as the increase in sensitivity which has been achieved. For example, in the Physical Eye Colorimeter the increase in sensitivity would be expected to increase the accuracy to which the shape of mask could be determined, particularly at the ends of the spectrum where very little light is available for measurement. If this can be achieved it may very considerably increase the accuracy of chromaticity measurements, whereas the increase in accuracy of luminous intensity or luminous flux measurements might not be appreciably improved except when measuring strongly coloured light sources, when the accuracy of a mask at the end of the spectrum is of great importance. As to whether the improvements in sensitivity at the very low

levels of illumination can be taken advantage of at the more normal levels, this will depend on the use of appropriate light attenuators; it may also be a question of economics, as the somewhat elaborate apparatus necessary for the counting technique may not always be justified.

Dr. Henderson's comments concerning the relative accuracy achieved in the I.E.C. interchange as compared with that shown in the paper are similar to Mr. Waigh's criticism and the reply is contained in my reply to Mr. Waigh. It is true that our mask type photometer colorimeter, with which both the photometric and colorimetric measurements were carried out, was calibrated by reference to N.P.L. calibrated tungsten filament secondary standard lamps. I believe that the Nela Park photometers were, as Dr. Henderson suggests, calibrated by reference to fluorescent lamps measured at the National Bureau of Standards.

As I indicated in my reply to Mr. Waigh, a better picture of the chromaticity discrepancies is obtained if one examines the departures from the mean of all members' measurements, particularly if the calculated chromaticities from the spectral distribution data from the Nela Park laboratories are included.

I am glad to note that Dr. Henderson is sympathetic towards further inter-comparisons as recommended by the C.I.E. at Zurich in 1955. It was with the results in mind which are quoted in my paper that I proposed the resolution at Zurich, which was subsequently agreed, that further inter-comparisons should be carried out on the photometry and colorimetry of fluorescent lamps with a view to reducing the present discrepancies.

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